

Recent mega-tsunamis in the Shark Bay, Pilbara, and Kimberley areas of Western Australia

P E PLAYFORD

Geological Survey of Western Australia, 100 Plain Street, East Perth, WA 6004, Australia. ✉ phil.playford@dmp.wa.gov.au

Very large blocks of calcrete, thought to have been the products of mega-tsunamis, lie on flat karstified calcrete surfaces behind coastal cliffs in the Shark Bay area and on Barrow and Legendre Islands. Some of these blocks weigh more than 700 t and are the largest such blocks known in the world. They are much too large to have been transported by cyclones. Other mega-tsunami deposits are known from the Kimberley, where they include large blocks of Proterozoic siliceous sandstone and mafic igneous rocks. The extremely jagged nature of the ria Kimberley coastline may have resulted, at least partly, from erosion by repeated impacts by mega-tsunamis, over millions of years. The tsunami deposits at Barrow and Legendre Islands include closely packed oyster shells, as encrustations on boulders of calcrete and small boulders composed of the shells alone. Two samples of oyster shells from Legendre Island, and seven from Barrow Island, have been radiocarbon dated as 2895 and 3777 years BP (Legendre Island) and 3498 to 5444 years BP (Barrow Island). The tsunamis that struck the Kimberley coast have not been dated, but are thought to have been repeated many times during the past few million years, associated with seismic activity along the Sunda and Banda Arcs of Indonesia. The origins of mega-tsunamis that impacted on the coast from Shark Bay to the Pilbara are uncertain. They are presumably too far away from the Sunda and Banda Arcs for earthquakes there to have been responsible, and it seems more likely that they originated from large-scale slumping of sediment on the continental slope (possibly initiated by earthquakes) or local faulting. Other less likely origins are underwater volcanism or asteroid impacts in the Indian Ocean.

KEYWORDS: Banda Arc, earthquake, neotectonics, radiocarbon dating, submarine slumping, Sunda Arc, tsunami.

INTRODUCTION

My interest in tsunami deposits began in 1977 when travelling in a small boat beside Legendre Island off the Pilbara coast. Many large blocks of limestone could be seen lying above low cliffs at the north end of the island, and it seemed possible that they had been thrown there by a large tsunami. In 2009, when sailing near Koks Island in Shark Bay, big limestone blocks could be seen lying on the flat surface of the island, and it seemed that these too could have been products of a large tsunami (Playford 2013). Furthermore, on several voyages along the Kimberley coast, during 2006–2010, evidence could be seen to indicate that mega-tsunamis had hit that coast many times in the recent past.

It was not until 2010, while conducting field work for a bulletin on the geology of Shark Bay, that it was feasible to investigate the deposits in the Shark Bay area. Subsequently, similar deposits were examined along the Pilbara and Kimberley coasts (Figures 1–3).

These mega-tsunami deposits are among the largest known in the world, and in the Shark Bay and Pilbara areas they are thought to have resulted from mega-tsunamis that tore away large blocks of Pleistocene calcrete from the tops of low coastal cliffs, carrying them up to several hundred metres inland. Radiometric dating of oyster shells from Legendre Island indicates that one such mega-tsunami occurred about 2900 years ago. The Kimberley deposits contain large blocks of Precambrian silicified sandstone and mafic igneous rocks.

Several authors have previously recognised tsunami deposits along the Western Australian coast, including Scheffers *et al.* 2008 who described deposits at Quobba Point that are also discussed here. Several publications on West Australian tsunami deposits (including Burbidge & Cummins 2007; Burbidge *et al.* 2008; Nott 2004; Nott & Bryant 2003) have described other tsunami deposits along this coast, but most of those deposits contain blocks that are much smaller than those recorded here.

Many publications have discussed issues involved in distinguishing between tsunami and storm deposits (including Nott 2003 a, b; Nott & Bryant 2003; Burbidge & Cummins 2007; Goto *et al.* 2011; Imamura *et al.* 2008; Sheffers *et al.* 2010; Paris *et al.* 2011; Nandasena *et al.* 2011; Goff & Chagué-Goff 2014). Goto *et al.* (2011) reported field evidence from Okinawa that recent storm waves there have lifted 100 t boulders over a reef and up onto cliff tops as much as 15 m high. They also drew attention to other accounts of storm waves pushing boulders weighing as much as 235 t. On the other hand, Nott & Bryant (2003) concluded that storm waves could barely move boulders weighing 20 t, and boulders heavier than that could only be lifted and transported by tsunami waves. No authors have claimed that blocks as large as those described here (weighing up to 700 t) could have resulted from storms rather than tsunamis. Nevertheless, Goff & Chagué-Goff (2014) have claimed that none of the deposits described by these authors in Western Australia should be interpreted conclusively as tsunami deposits, as they could have resulted from intensive cyclones. I disagree with this conclusion, but as their paper only came to my attention when the present

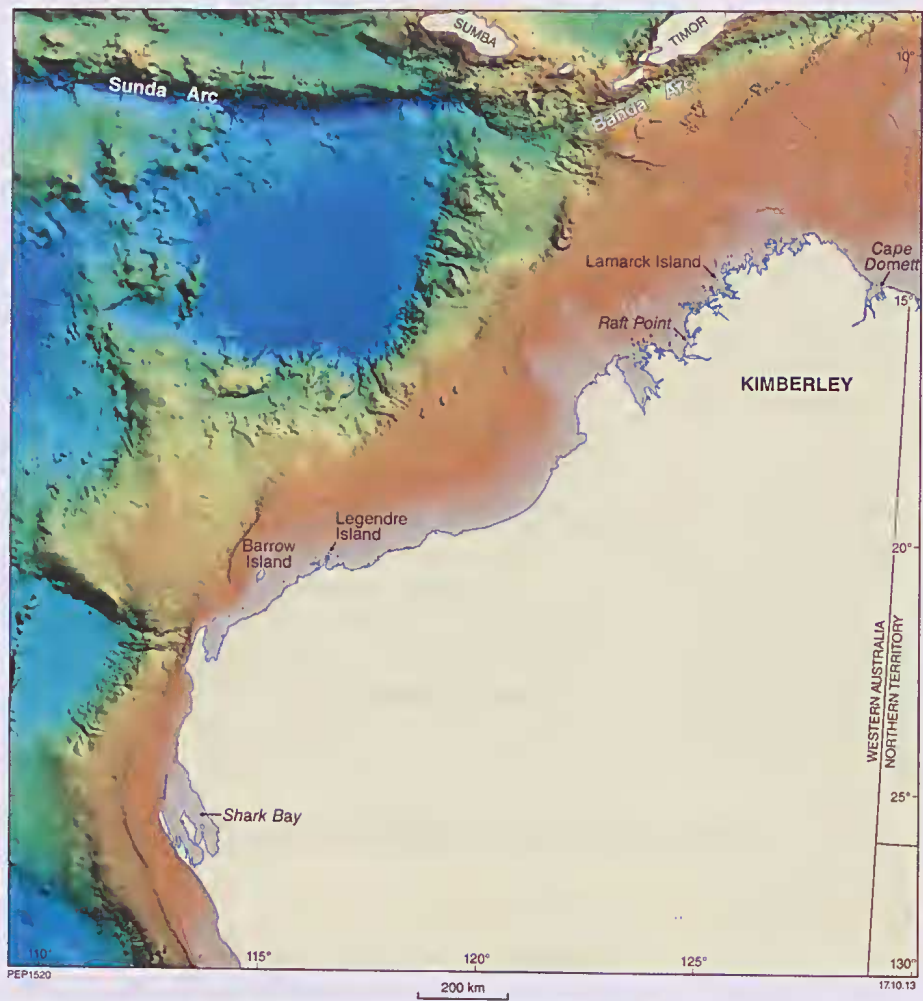


Figure 1 Map of part of Western Australia and its adjoining offshore area, from Geoscience Australia's map 'Surface Geology of Australia', showing the submarine topography and locations of mega-tsunami deposits in the Shark Bay, Barrow Island, Legendre Island, and Kimberley areas.

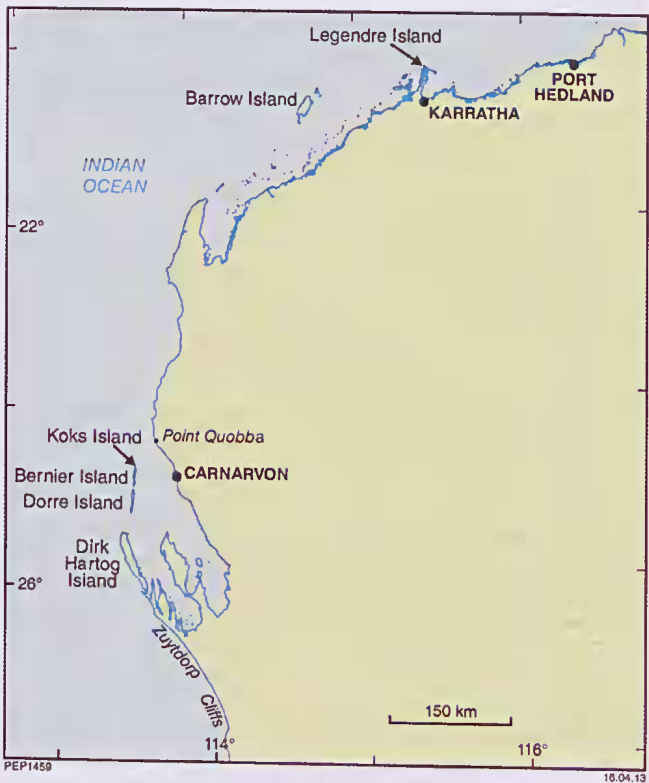


Figure 2 Map showing localities between the Zuytdorp Cliffs and Legendre Island where boulder deposits were emplaced by mega-tsunamis that hit the coast a few thousand years ago.

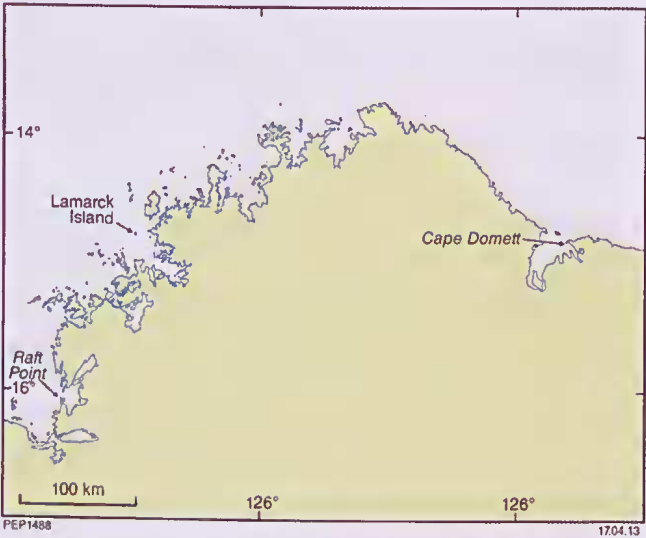


Figure 3 Map of the Kimberley showing the extremely jagged nature of the coast and the locations of photos included in the text. This jagged coastline may have partly resulted from repeated impacts by mega-tsunamis, over millions of years.



Figure 4 'The Block', situated beside the west coast of Dirk Hartog Island, 6.5 km southwest of Cape Inscription. This calcrete block measures 10.5 x 8 x 4 m, and is estimated to weigh at least 700 t. It was derived from the top of the shoreline cliff and thrown by a mega-tsunami about 15 m above sea level and 120 m behind the cliff.



Figure 5 Aerial view of a group of closely spaced imbricate calcrete blocks, on the west coast of Dirk Hartog Island, 15 km south-southwest of Cape Inscription, looking north. The largest block measures 13 x 7.5 x 3 m, and weighs about 700 t. These blocks rest on a strongly karstified calcrete surface behind a cliff about 5 m high. They slope away from the coast, and were oriented in this way by the powerful backwash that followed the tsunami.



Figure 6 View of several of the calcrete blocks shown in Figure 5, showing their strong imbrication, sloping east, away from the coast, as a consequence of the backwash that followed the tsunami. Note the wedge shapes of the blocks, which resulted from abrasion as each block was pushed across the karstified land surface by the powerful backwash. Photo by Shaun Coldicutt.



Figure 7 Aerial view looking south over Cape Inscription on Dirk Hartog Island, (beside the place where Dirk Hartog landed in 1616), showing many angular slabs of calcrete (calcretised eolianite) lying on the cliff slope and at its base. These boulders are thought to have been dislodged by a mega-tsunami. Note that the numbers of blocks at the base of the cliffs decrease moving south from the headland.

paper was at the proof stage, it is not practicable to discuss the issues they raised in more detail.

Burbidge *et al.* (2008) pointed out that Western Australia has experienced five significant tsunamis in historic times. The largest, resulting from the 2006 Java earthquake, had a runup (height reached above sea level) of 9 m. Campers at Steep Point (at the northern end of Edel Land Peninsula) were lucky to escape, uninjured, from this tsunami. Burbidge *et al.* also reported that as a result of the Boxing Day Tsunami of 2004 (which originated at the northwest end of the Sunda Arc),

bathers beside some Western Australian beaches were dragged out to sea, but all managed to survive.

DIRK HARTOG ISLAND

Many boulder deposits that resulted from two or perhaps three tsunamis are recognised along the west coast of Dirk Hartog Island (Figures 4–6). They include huge blocks of limestone (calcrete), weighing many hundreds of tonnes. The largest of the blocks, known colloquially as 'The Block', is situated 6.5 km southwest of Cape



Figure 8 Photos taken in 1910 (top) and 2010 (bottom) of part of the scarp at Cape Inscription, looking north. They show large blocks of calcrete, up to several metres across, jumbled together at the foot of the cliff, and a thick calcrete layer at the cliff top. These large blocks have not moved during the past 100 years, despite many tropical cyclones having passed over or near Cape Inscription during that period. The SS Minilya, a State steamship last used there in 1910, can be seen in the top photo, which was taken by Adjee Cross.



Figure 9 Weathered boulders of calcrete on the west side of Dirk Hartog Island, about 200 m from the cliff face and 20 m above sea level. This deposit is thought to have resulted from a tsunami older than that responsible for the large boulders shown in Figures 4–6.



Figure 10 A deposit of small boulders, beside the coast south of Cape Inscription, that may have resulted from a very recent tsunami, although a severe storm could have been responsible.



Figure 11 Aerial view looking southwest over Koks Island, showing scattered boulders lying on the flat karstified surface. A large block lies perched on top of the cliff at the south end of the island. These blocks are thought to have been wrenched by a mega-tsunami from the two U-shaped re-entrants on the north side of the island.



Figure 12 Blocks of limestone thrown up by a mega-tsunami behind the low shoreline cliff at Point Quobba.



Figure 13 Composite air photo of Barrow Island showing the locations of oyster-shell samples collected from tsunami deposits, the radiocarbon ages of which are listed in Table 1.

Inscription (Figure 4). It measures 10.5 x 8 x 4 m and is estimated to weigh at least 700 t. The mega-tsunami that carried these blocks is thought to have been at least 20 m high, with a runup on the land of more than 30 m, reaching hundreds of metres inland.

Calcrete blocks of comparable dimensions to 'The Block' are known at other places behind coastal cliffs along the northwest coast of the island. These blocks were torn from the cliffs and carried inland. At one place on the west side of the island there is a conspicuous group of closely spaced, wedge-shaped, imbricate blocks, sloping east, away from the coast (Figures 5, 6). Those blocks must have been thrown inland by the tsunami and then dragged back, towards the sea, by the huge backwash that followed. Abrasion of these blocks on the rough karstified calcrete surface resulted in their wedge shapes, with the upper surfaces dipping away from the sea. Such large-scale imbrication, thought to have resulted from the backwash of a tsunami, has not been reported elsewhere in the world.

Where the coastal cliffs are higher than about 15 m, blocks thought to have been dislodged by one or more mega-tsunamis have not been carried over the cliffs, but have remained on the cliff slopes or rest jumbled together at their base (Figures 7, 8). Although some of the blocks at those places could have resulted from normal subaerial collapse, most are probably tsunami-derived.

Deposits of smaller and more weathered boulders (maximum about 3 m across), extend as far as 200 m from the cliff face and about 20 m above sea level (Figure 9). They are thought have resulted from an earlier mega-tsunami, even larger than the one discussed above.

Another deposit of much smaller boulders occurs close to the coast, up to about 2 m above sea level, southwest of Cape Inscription (Figure 10). It must be younger than the other deposits described above. The boulders, measuring up to 2.3 x 1.5 x 0.5 m, and weighing as much as 3 t, are very angular and unweathered. This deposit may have resulted from a very recent tsunami, much smaller than the other two. However, a major cyclone cannot be ruled out as the source, because of the relatively small size of the boulders that the deposit contains.

Some sandy deposits, thought to be tsunami-derived, are situated near the north coast of the island. Those deposits are up to 30 m above sea level, and contain large molluscs and small clumps of corals. Corals from one of these clumps have been radiocarbon dated as 4004±41 years BP. In contrast, a *Tridacna* (giant clam) shell in these sandy deposits returned a date of 38 522±605 years BP (Table 1), illustrating one of the problems involved in dating tsunami deposits. The organism in this shell must have died that long ago, before being swept up by a recent tsunami.

Photographic evidence shows that large boulders at the foot of the cliff at Cape Inscription, thought to have been dislodged from the calcrete layer at the top of the cliff by a mega-tsunami, have not moved during the past 100 years, despite at least seven tropical cyclones having passed over, or within 50 km of, Cape Inscription during that period (Figure 8). This observation is consistent with the interpretation that the large blocks there have been dislodged by a mega-tsunami rather than a storm.

DORRE AND BERNIER ISLANDS

Large blocks of calcrete commonly lie on subhorizontal surfaces behind coastal cliffs along the west coasts of Dorre and Bernier Islands, at places where the cliffs are not more than about 15 m high. These blocks have been carried as far as 300 m inland. Many very large blocks, apparently derived from the impacts of one or more mega-tsunamis, lie at the base of the cliffs or are plastered on the cliff slopes.

KOKS ISLAND

Koks Island is a small island (about 140 x 280 m), immediately north of Bernier Island. Many blocks, the largest measuring about 8 x 6 x 4 m, and weighing about 500 t, rest on a flat calcrete surface about 10 m above sea level. One block lies perched on top of the cliff at the

Table 1 Results of radiocarbon dating of tsunami deposits on Dirk Hartog, Legendre and Barrow Islands.

Sample no.	Locality	Description	Elevation (approx)	Age (years BP)
135221	Dirk Hartog Island 697952E 7180228N	Clump of coral over red sand	30 m	4004 ± 41
135219	Dirk Hartog Island 695968E 7177900N	<i>Tridacna</i> shell	27 m	38 522 ± 605
135239	Legendre Island 482630E, 7749047N	Small block of oyster shells	4 m	2895 ± 35
135240	Legendre Island 482630E, 7749047N	Larger block of oyster shells	4 m	3777 ± 40
135270 (3A)	Barrow Island 325470E, 7697835N	Oyster shells encrusted on block of calcrete	5 m	5444 ± 37
135271 (3B)	Barrow Island 325470E 7697835N	Oyster shells encrusted on block of calcrete	5 m	4586 ± 37
135272 (6A)	Barrow Island 336760E 7713650N	Block of oyster shells	3 m	5245 ± 38
135273 (6B)	Barrow Island 336760E 7713650N	Block of oyster shells	3 m	3498 ± 36
135274 (8A)	Barrow Island 325530E 7697960N	Oyster shells encrusted on block of calcrete	8 m	4091 ± 39
135275 (8B)	Barrow Island 325530E 7697960N	Oyster shells encrusted on block of calcrete	8 m	4652 ± 28
135277 (8D)	Barrow Island 325530E 7697960N	Oyster shells encrusted on block of calcrete	8 m	4571 ± 41

Analyst: University of Waikato Radiocarbon Dating Laboratory



Figure 14 Boulders of calcrete about 7 m above sea level on the west coast of Barrow Island, interpreted to have been derived from a mega-tsunami. Photo by Russell Lagdon.



Figure 15 Boulder of calcrete encrusted with closely packed oyster shells, on the west coast of Barrow Island. The oysters grew into pre-existing karst holes on the block, pointing to its complex history, as discussed in the text.

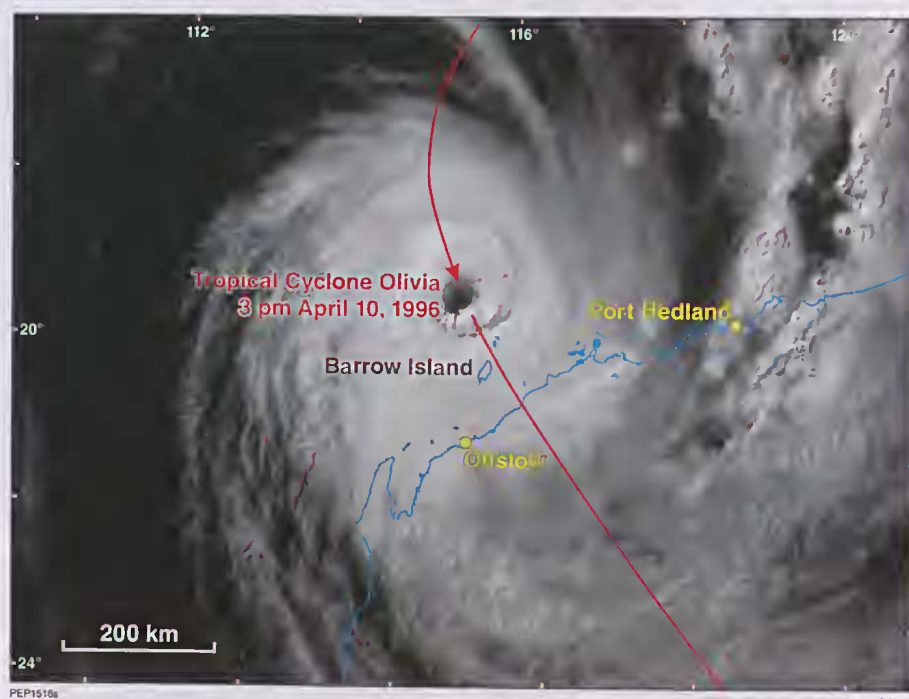


Figure 16 Image showing the path of Cyclone Olivia, an intense tropical cyclone that passed close to Barrow Island on April 10, 1996, generating the largest wind gust ever recorded on earth.

south end of the island. These blocks have apparently been derived from two U-shaped indentations in the cliff at the north end of the island (Figure 11).

On early charts of Shark Bay this island is labelled as 'Koks Island (boulders)', no doubt because the blocks on the flat top of the island are very conspicuous when viewed from a ship.

ZUYTDORP CLIFFS

No deposits that can unequivocally be interpreted as tsunami deposits have been identified along the Zuytdorp Cliffs. Those cliffs constitute a fault-line scarp that extends for nearly 200 km between Kalbarri and Steep Point (Playford *et al.* 2013). The cliffs, from 30 m to 260 m high, are too high to have allowed blocks of limestone to be carried up and over them by a mega-

tsunami. However, it is possible that many of the boulders lying on or below the cliff slopes have been dislodged by mega-tsunamis. Moreover, some sandy deposits on top of cliffs about 30 m high along this coast contain many marine shells and have hitherto been interpreted as Aboriginal kitchen middens (Morse 1988; Playford 1996). However, it seems possible that they are instead tsunami deposits, a hypothesis that remains to be tested in the field.

POINT QUOBBA

Large blocks of calcrete and calcretised eolianite rest on flat, bare, karstified calcrete surfaces behind coastal cliffs about 5 m high, on the mainland coast and a small island at Point Quobba, near the north end of the Shark Bay (Scheffers *et al.* 2008) (Figure 12). The largest block on the

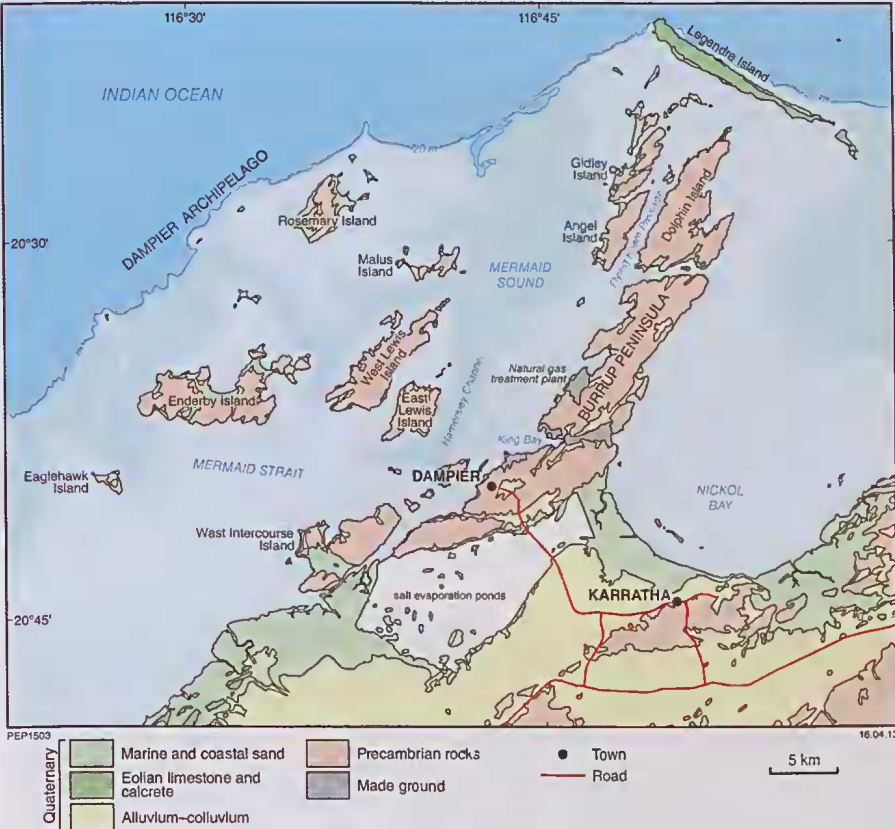


Figure 17 Geological map of the Burrup Peninsula area, showing the locations of Legendre Island, the towns of Karratha and Dampier, and the LNG facility.



Figure 18 Aerial view looking north over the northwest end of Legendre Island, showing large calcrete blocks deposited by a mega-tsunami about 2900 years ago, resting on a strongly karstified calcrete surface.



Figure 19 View on the ground of the large blocks of calcrete shown in Figure 18, lying on a strongly karstified calcrete surface. The largest of these blocks, on the skyline, is 12.5 m long.



Figure 20 Aerial view of part of the northwest coast of Legendre Island, showing sculpting of the cliff face attributed to one or more mega-tsunamis, with many blocks of calcrete lying scattered over the land surface and extending up to 300 m behind the cliff.

mainland is estimated to weigh about 70 t, only one tenth of the size of the largest blocks on Dirk Hartog Island. The smaller size of the blocks at Point Quobba can be explained by the fact that the tsunami wave in reaching there had passed over water much shallower than on the west side of Shark Bay, and this shallowing had reduced the size of the tsunami.

Scheffers *et al.* (2008) described several tsunami deposits on the west coast of Australia between Cape

Range and Point Quobba. They recorded blocks at Point Quobba that were torn from coastal cliffs and the adjacent sea floor and carried more than 200 m inland and 5–7 m above sea level. Some blocks derived from the sea floor are extensively bored by bivalves and the bivalve shells have been radiocarbon dated as 610–1670 years BP (Scheffers *et al.* 2008). Those authors also determined that at least one earlier tsunami event had occurred in that area, about 5700 years ago.



Figure 21 A column of silicified sandstone in a fault zone near Cape Domett, looking south, showing two reddish-orange boulders of silicified sandstone perched near the top of the column, about 9 m above ground level and 12 m above sea level. They may have been deposited there by a mega-tsunami that moved from the north.



Figure 22 Boulder deposit on the east (lee) side of Lamarck Island. The boulders in this deposit are thought to have been torn from the west coast of the island and carried to this site by a mega-tsunami.

BARROW ISLAND

Barrow Island is the site of a producing oilfield, and a major liquefied-natural-gas (LNG) facility is now being built there to process gas from Chevron Australia's gasfields west of the island (Figure 13). A two-day visit was made to the island in May 2013, accompanied by Russell Lagdon, Environment Manager of Chevron.

Boulder deposits occur at various localities above and below coastal cliffs along the west coast of the island (Figures 14, 15). They consist of calcrete blocks up to 5.2 x 2.5 x 2.0 m in size and about 60 t in weight. Some blocks are encrusted with closely packed oyster shells; others consist entirely of such shells. The calcrete boulders are significantly smaller and more eroded, and appear to be older than those on Legendre Island and in the Shark Bay area. Oyster shells were collected for radiocarbon analysis at three localities. They returned ages of 3498 to 5444 years BP (Table 1). There is no clear explanation for such a large range in dates, but perhaps they point to at least three mega-tsunamis that occurred about 3500, 4100 and 5250 years BP. More detailed field work and radiocarbon datings will be needed to resolve this issue.

Some of the oyster encrustations are on pre-existing boulders of karstified calcrete, and the oyster shells extend into karst holes on those boulders (Figure 15). These boulders may have been carried onto the sea floor by the backwash of an earlier tsunami, then encrusted by oysters, and finally thrown up by another tsunami. It seems that the history of these tsunami deposits is very complex.

The edge of the continental shelf west of Barrow and Legendre Islands forms a steep scarp (Fig. 1). This is due to periodic collapse, possibly associated with faulting (Hengesh *et al.* 2013), and the resulting slides may have been responsible for the mega-tsunamis that are evidenced on those islands.

It is important to note that on 10 April 1996 an intense tropical cyclone, Cyclone Olivia, passed over Barrow Island (Figure 16). The strongest gust of wind ever recorded on earth (408 km/hour) was registered on the island during the passage of that cyclone (Courtney *et al.* 2012). Despite its extreme strength, this cyclone had no discernible effects on existing boulder deposits, nor is it known to have resulted in any new boulder deposits (Russell Lagdon pers. comm. 2013).

LEGENDRE ISLAND

Legendre Island, 15 km long and up to 1.5 km wide, is situated off the Pilbara coast, north of the Burrup Peninsula and near the towns of Dampier and Karratha, some 700 km north-northwest of Shark Bay (Figure 17). Huge blocks of calcrete rest on a flat calcrete surface in the north and northwest parts of the island (Figures 18–20), behind a jagged coastline of coastal cliffs thought to have been sculpted by mega-tsunamis. The blocks may be the products of one or more mega-tsunamis, but it is not known whether they were contemporaneous with any of those that struck Barrow Island and the coast of Shark Bay.

The largest of the calcrete blocks on Legendre Island

measures 12.5 m x 5 m x 4 m, is estimated to weigh more than 600 t, and lies about 8 m above sea level. These huge blocks must have been torn from the low cliffs along the north and northwest coasts of the island. Smaller blocks of oyster limestone also occur in the deposits, and these were apparently derived from oyster ridges that fringed shoreline platforms on the north side of the island. Two samples of the oyster blocks have been radiocarbon dated as 2895 and 3777 years BP (Alan Hogg pers. comm. 2010) (Table 1). The younger of those dates, rounded to 2900 years, may be the approximate date of the last tsunami, but many more dates are needed to test that conclusion.

KIMBERLEY COAST

Many deposits containing large blocks of silicified sandstone are present along the ria ('drowned') Kimberley coast, and are interpreted to have resulted from mega-tsunamis (Figures 1, 3, 21–24). The presence of such deposits is not unexpected in view of the proximity of the Kimberley to one of the world's most active seismic zones, the Sunda Arc beside Indonesia (Figure 24) (Hengesh *et al.* 2010). The adjoining Banda Arc is much less active, but large earthquakes do occur there periodically. At their closest, these arcs are less than 500 km from the Kimberley, and large earthquakes originating there can be expected to have generated tsunamis that may have had important roles in sculpting the jagged Kimberley coast. A mega-tsunami caused by a large earthquake along the closest parts of those zones could reach the Kimberley in about an hour. The same mega-tsunami, with progressively decreasing strength, would take more than two hours to reach the Pilbara and three hours to reach Shark Bay.

ORIGIN OF THE MEGA-TSUNAMI DEPOSITS

It has not been possible to link mega-tsunamis in the Shark Bay area, Barrow Island and Legendre Island with any of those that struck the Kimberley. Although mega-tsunami deposits in the Kimberley area are likely to have been generated by earthquake activity along nearby parts of the Sunda and Banda Arcs, those arcs are thought to be too far away to have been responsible for the mega-tsunami deposits along the Pilbara and Shark Bay coasts. Perhaps the most likely explanation for the origin of those deposits is massive slumping of sediments from scarps along the edge of the continental shelf (Figure 1: Hengesh *et al.* 2012; Bondevic *et al.* 2013; Scarselli *et al.* 2013). Such slumping may have been initiated by local earthquake activity. Other possible explanations are local faulting or (less likely) underwater volcanism and asteroid impacts in the Indian Ocean.

HUMAN AND FAUNAL CONSEQUENCES

The mega-tsunamis responsible for the boulder deposits in the Shark Bay, Barrow Island, Legendre Island and Kimberley areas were probably the most catastrophic events to affect Western Australia during the past 6000 years. They may have caused the deaths of thousands of Aborigines and animals then living in coastal areas. An



Figure 23 Cliff face of a small island near Raft Point in the Kimberley, surrounded by a wide band of very large angular boulders of siliceous sandstone, thought to have been dislodged by mega-tsunami impacts.

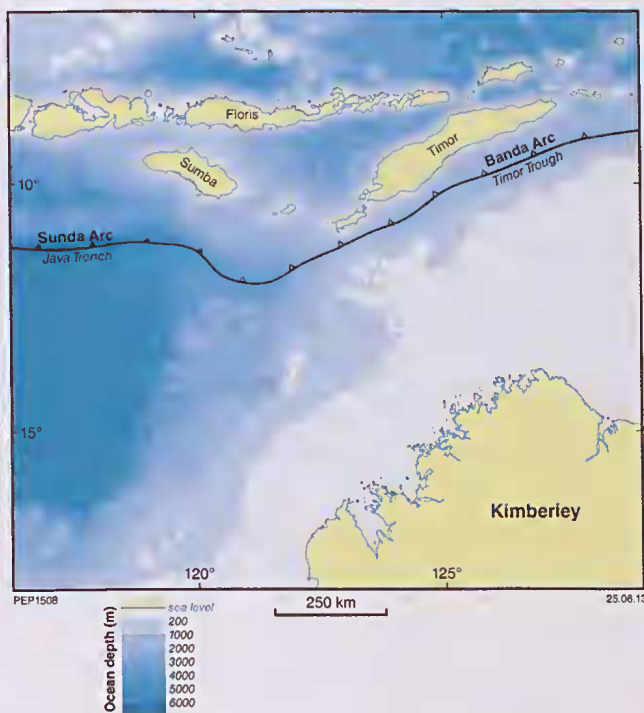


Figure 24 Map showing the Kimberley and parts of the Banda and Sunda Arcs, beside the Indonesian Archipelago. The intricately sculpted ria coastline of the Kimberley may have resulted from repeated impacts by mega-tsunamis resulting from earthquakes along the Sunda and Banda Arcs.

Aboriginal account of a 'big wave' that swept across the Montgomery Islands (in the Kimberley), probably during the early 20th century, is thought to have killed about 300 Aborigines, with only two survivors (Playford *et al.* 2013).

Another mega-tsunami could strike the coast of Western Australia at any time, although it may not eventuate for thousands of years. If such an event were to be repeated now, it would have devastating consequences for communities, towns and industries in some coastal areas.

ACKNOWLEDGEMENT

This paper includes many illustrations from Playford *et al.* (2013), and is published with the permission of the Director, Geological Survey of Western Australia.

REFERENCES

- BONDEVIC S, MANGERUD J, DAWSON S, DAWSON A & LOHNE Ø 2003. Record-breaking height for 8000-year-old tsunami in the North Atlantic. *Eos* 84, 289–300.
- BURBIDGE D. & CUMMINS P R 2007. Assessing the threat to Western Australia from tsunami generated by earthquakes along the Sunda Arc. *Natural Hazards* 43, 319–331.
- BURBIDGE D, CUMMINS P R, MLECKZO R & THIO H K 2008. A probabilistic tsunami hazard assessment for Western Australia. *Pure and Applied Geophysics* 165, 2059–2088.

- COURTNEY J, BUCHAN S, CERVENY R S, BESSEMOULIN P, PETERSON T C, RUBIERA J M, TORRES J, BEVAN J, KING J, TREVEN B & RANCOURT K 2012. Documentation and verification of the world extreme gust of wind record: 113.3 ms⁻¹ on Barrow Island, Australia, during passage of tropical cyclone Olivia. *Australian Meteorological and Oceanographic Journal* 62, 1–9.
- GOFF J & CHAGUÉ-GOFF C 2014. The Australian tsunami database: a review. *Progress in Physical Geography* 38, 218–240.
- GOTO K, MIYAGI K, KAWANA T & IMAMURA F 2011. Emplacement and movement of boulders by known storm waves — field evidence from the Okinawa Islands, Japan. *Marine Geology* 283, 66–78.
- HENGESH J V, DIRSTEIN J K & STANLEY A J 2012. Seafloor geomorphology and submarine landslide hazards along the Continental Slope in the Carnarvon Basin, Exmouth Plateau, North West Shelf, Australia. *APPEA Journal* 2012, 493–512.
- HENGESH J V, DIRSTEIN J K & STANLEY A J 2013. Landslide geomorphology along the Exmouth Plateau continental margin, North West Shelf, Australia. *Australian Geomechanics Society* 48(4), 71–92.
- HENGESH J, WYRWOLL K-H & WHITNEY B B 2010. Neotectonic deformation of northwestern Australia: implications for oil and gas development. Proceedings of the 20th Annual Australian Earthquake Engineering Society Conference, Perth <http://www.aees.org.au/Proceedings/2010_Papers/22-Hengesh.pdf>
- IMAMURA F, GOTO K & OHKUBO S. 2008. A numerical model for the transport of a boulder by tsunami, *Journal of Geophysical Research* 113, C01008, doi:10.1029/2007JC004170.
- MORSE K 1988. An archaeological survey of midden sites near the Zuytdorp wreck, Western Australia. *Bulletin of the Australian Institute for Maritime Archaeology* 12, 37–40.
- NANDASENA N A K, PARIS R & TANAKA N 2011. Reassessment of hydrodynamic equations: minimum flow velocity to initiate boulder transport by high-energy events (storms, tsunamis). *Marine Geology* 281, 70–84.
- NOTT J 2003a. Tsunami or storm waves? Determining the origin of a spectacular field of wave-emplaced boulders using numerical storm surge and wave models and hydrodynamic transport equations. *Journal of Coastal Research* 19, 348–356.
- NOTT J 2003b. Waves, coastal boulder deposits, and the importance of pre-transport settings. *Earth and Planetary Science Letters* 210, 269–276.
- NOTT J 2004. The tsunami hypothesis — comparisons of the field evidence against the effects on the Western Australian coast of some of the most powerful storms on earth. *Marine Geology* 208, 1–12.
- NOTT J & BRYANT E. 2003. Extreme marine inundations (tsunamis?) of coastal Western Australia. *Journal of Geology* 111, 691–706.
- PARIS R, NAYLOR L A & STEPHENSON W J 2011. Boulders as a signature of storms on rock coasts. *Marine Geology* 283, 1–11.
- PLAYFORD P E 1996. *Carpet of Silver, the wreck of the Zuytdorp*. University of Western Australia Press, Perth.
- PLAYFORD P E 2013. Recent mega-tsunamis in the Shark Bay, Pilbara and Kimberley areas of Western Australia. *Western Wildlife* 17(4), 1, 4, 5.
- PLAYFORD P E, COCKBAIN A E, BERRY P F, ROBERTS A P, HAINES P W & BROOKE B P 2013. The geology of Shark Bay. *Geological Survey of Western Australia Bulletin* 146.
- SCARSELLI N, McCLAY K & ELDERS C 2013. Submarine slide and slump complexes, Exmouth Plateau, NW Shelf of Australia. In: Keep M & Moss S J (eds) *The Sedimentary Basins of Western Australia IV*, pp. 1–20. Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth WA, 2013.
- SCHEFFERS A, KELLETAT D, HASLETT S, SANDER S, SCHEFFERS S R & BROWNE T 2010. Coastal boulder deposits in Galway Bay and the Aran Islands, western Ireland. *Zeitschrift für Geomorphologie* 54, Suppl. 3, 247–279.
- SCHEFFERS S R, SCHEFFERS A, KELLETAT D & BRYANT E A 2008. The Holocene paleo-tsunami history of West Australia. *Earth and Planetary Science Letters* 270, 137–146.

Received 11 September 2013; accepted 6 November 2013 (note added in proof 9 June 2014)